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RESEARCH MEMORANDUM

EFFECT OF ENGINE AND CONTROL LIMITS ON STEADY-STATE AND TRANSIENT PERFORMANCE OF TURBOJET ENGINE WITH VARIABLE-AREA EXHAUST NOZZLE

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SUMMARY

Steady-state and transient characteristics of the J34-WE-32 turbojet engine with electronic power regulator were obtained in the NACA Lewis altitude wind tunnel to determine the effects of engine and control limits on the performance.

Limits on the fuel valve and exhaust nozzle area influence any schedule of speed and temperature. When either or both of these inputs are at a limit, the engine operates off the reference schedule. This deviation of speed and temperature from the reference or set values can result in a nonlinear variation of thrust with power lever position, a reversal of the thrust-power lever relation, a dangerous condition at low power because of rising temperatures, and a ceiling which is below the capabilities of the engine and varies with power lever position. These difficulties are encountered chiefly at high altitudes, low power lever positions, or a combination of both. The extent to which such difficulties apply to actual operation in flight will depend, of course, on the specifications of range of altitudes and Mach numbers over which each particular aircraft must operate. In addition, the types of power lever movements or positions necessary for operation at any flight condition must be considered. Some of the difficulties discussed herein may be outside the specified range of operation of a particular aircraft. Other difficulties may be avoided during flight by restricting the range of allowable power lever movement, especially at high altitudes. As the operational altitude of present and future aircraft increases, however, the problems discussed in this report will become increasingly important, and means for avoiding them should be considered.

For the control system studied, one possible solution of the problems is to lower the minimum fuel flow setting and to introduce an overtemperature signal to the exhaust nozzle. These changes would eliminate or lessen the previous difficulties but would cause trouble due to blowout during transient operation. A device designed specifically to counteract this problem would also be needed.

A better solution appears to be the addition of a device to change the set speed schedule with the flight condition. This would eliminate the need for a high minimum fuel flow setting as well as alleviate the

problems of steady-state operation. Furthermore, the transient characteristics of the engine need not be affected by this change but can be made comparable with those obtained by using a high minimum fuel flow.

INTRODUCTION

An investigation of the Westinghouse J34-WE-32 turbojet engine and control was conducted in the NACA Lewis altitude wind tunnel. The over-all object of the program was to determine steady-state and dynamic characteristics of the engine and to evaluate the operational performance of the controlled system at various altitudes and ram pressure ratios. 2409

The control or power regulator of this engine is an electronic device that provided a multiloop system in which both engine speed and temperature were controlled by varying fuel flow and exhaust nozzle area. In order to obtain over-all steady-state operation in a desired manner, both required speed and temperature are scheduled as functions of throttle or power lever position.

While obtaining data for the controlled engine, it became evident that the minimum fuel flow setting of 550 pounds per hour specified by the manufacturer limited the range and stability of engine operation. Because of this limited range and oscillatory operation at high altitude, data were taken with lower minimum fuel flow settings of 420 and 350 pounds per hour.

The present report illustrates the effect of the minimum fuel flow setting and other engine and control limits on the steady-state and transient operation of the system. Steady-state data showing variations of speed and temperature as well as other parameters at the different settings are presented for altitudes of 10,000, 25,000, 35,000, and 45,000 feet at a ram pressure ratio of 1.2. Additional data are given showing the safe operating range of the engine as a function of altitude. Oscillographic traces of the response of several engine parameters to a step change in throttle position for some of these flight conditions are also presented.

DESCRIPTION OF CONTROL

Schedule. - The output thrust of this system was controlled by introducing scheduled values of both engine speed and turbine discharge temperature into the control as functions of throttle position.

The engine speed schedule was designed to be constant from cut-off, which was 21° on the power lever, to 26°, then to rise sharply to 43°, followed by a slower rise to 71°. Beyond 71°, the schedule required that maximum engine speed be maintained. The temperature schedule was constructed to be constant from cut-off to 26°, then to follow a smooth

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curve rising slowly at first from 26° and then more rapidly to 82°, which represented full military thrust without afterburning. Beyond 82°, the temperature was scheduled at the maximum allowable value. The region from 21° to 26° is designated the idle flat spot on the power lever and that from 82° to 89°, the military flat spot.

Design of the reference schedule was such as to provide approximately linear thrust at sea level as a function of throttle position.

Block diagram. - A block diagram of the control system is shown in figure 1. It can be seen that, basically, engine fuel flow is controlled by a summation of speed, temperature, and overtemperature error signals, and area is controlled by a summation of speed and temperature error signals. The control is of the proportional plus integral type and additional features in the form of "limits" have been added to obtain proper control action during dangerous or special operational conditions. All indicated limiting devices in figure 1 have been designated in their respective blocks with a plot of the specific output against input characteristics of the unit. The fuel valve and exhaust nozzle blocks show the limits resulting from mechanical stops which determine the maximum opening or minimum closing of the mechanism.

Fuel Valve Limit

This minimum setting was incorporated into the fuel control system for two basic reasons: (1) to establish sufficient fuel flow for sea-level starting and (2) to force an increase in idle speed as a function of altitude sufficient to allow acceptable transient performance. As a result of this setting, however, the fuel valve was on the minimum flow stop for a wide range of power lever settings at high altitudes. Under these circumstances the effectiveness of the fuel control was completely lost and the only control remaining was primarily that of engine speed by exhaust nozzle area.

Exhaust Nozzle Limits

In the case of the exhaust nozzle it is the fully open stop which causes off-schedule performance. The nozzle becomes less effective as a control on speed and temperature as it is opened. Its usefulness is lost completely when the effective nozzle area approaches the area of the turbine exit annulus. Any system using the exhaust nozzle area as a control variable will have these basic engine limitations imposed upon it.

Overtemperature Limit

The remaining limits shown in figure 1 were incorporated in the electronic phase of the control. The overtemperature limit operates in such a manner that it adds no signal to the fuel loop as long as normal temperature is developed in the engine, but it does add a signal to decrease fuel flow when temperatures over 1250° F prevail at the turbine outlet. At high altitudes, of course, where the fuel valve is on its closing stop, the overtemperature protection feature of the control can no longer function. 2409

Speed Error Limit

If the aforementioned overtemperature condition occurred when speed was below the set value, the speed error would be calling for an increase in fuel flow, which is contrary to what is desired to reduce overtemperature. Another limiter is therefore used on the speed error signal to restrict its effect on fuel flow.

Temperature Error Limits

As lower thrust is required, the schedule is set by the throttle to require low engine speed and temperature. It is characteristic of turbojet engines, however, that speed and temperature decrease until some speed is reached after which temperature increases with a further reduction in speed. Such a reversal in slope imposes the problem of controlling through the zero slope region and of providing a reversal of sign in the control whenever a reversal of slope occurs in the engine in order to maintain a stable system. Therefore, because it is not possible to operate at both low speed and low temperature, the choice was made to limit the temperature error. This limit on temperature error, together with the proper proportioning of signals to the fuel valve servo and the relative ineffectiveness of the exhaust nozzle on speed and temperature at low speeds, causes the control to be essentially one of speed by fuel flow at low power. The temperature rises to whatever value is consistent with the fuel flow. It is also desirable to open the exhaust nozzle area on acceleration in order to improve response time and to avoid entering the compressor stall or surge region. During an acceleration, the large speed error acts to increase the exhaust nozzle area, but the temperature error would tend to decrease this area. Accordingly, another limit on temperature error is required to reduce the effectiveness of a large temperature error signal so that speed error can force the exhaust nozzle area open and hold it there as long as a large speed error is available. When the engine reaches required speed and speed error is reduced, the temperature error again becomes effective and closes the

exhaust nozzle area to establish the set temperature.

APPARATUS

Engine. - The J34-WE-32 turbojet engine used in this investigation has an 11-stage axial-flow compressor, double annular combustor, two-stage turbine, and variable-area exhaust nozzle. The polar moment of inertia of the complete rotor about the rotor axis is 79.8 pound-feet
2409 squared. Full military thrust under sea-level static conditions requires 3640 pounds per hour of fuel.

Control. - The Westinghouse electronic power regulator, part no. 61-F-758-4, serial no. S-CZA-78, modified to correspond to part no. 61-F-758-6 insofar as temperature schedule is concerned, was used as the control.

The investigation was conducted with three different values of minimum fuel flow set into the control - first with 550 pounds per hour, which was specified by the manufacturer, and then with 420 and 350 pounds per hour. The setting in each case was adjusted at 2000 feet of altitude with the engine windmilling at 1500 rpm. These conditions were chosen in order to obtain reproducible settings because actual fuel flow varied as a function of engine speed when the valve was on a minimum stop.

The original thermocouple harness of nine paralleled short thermocouples was removed and replaced by another group of nine paralleled elements which were immersed 6 inches. The thermocouples were of equal resistance to insure more nearly average temperature indication.

Test facilities. - The investigation was conducted in the Lewis altitude wind tunnel with a 20-foot-diameter test section. Air was supplied through a ram pipe connected directly to the engine.

Instrumentation. - Engine parameters were recorded during transients on multiple channel, direct inking, magnetic penmotor oscillographs having a chart speed of 2.5 units per second. The penmotor in combination with its amplifier has an essentially flat frequency response to approximately 100 cycles per second. Detailed information on the transient instrumentation employed is presented in reference 1. Table I lists the engine parameters that were recorded, the intrumentation used to measure the values of the parameters in the steady state, the sensing devices used to measure the variations in the parameters during transients, and the frequency response range of the transient instrumentation. Exhaust nozzle

position was indicated by a microammeter, which in turn was calibrated against exhaust nozzle area as shown on figure 2.

PROCEDURE

Steady-state data. - Steady-state data of the controlled engine were taken with various power lever positions at altitudes of 10,000, 25,000, 35,000, and 45,000 feet at a ram pressure ratio of 1.2. These tests were performed for three minimum fuel-flow settings of 550, 420, and 350 pounds per hour. 2409

Additional steady-state data were taken to determine the safe operating range of the engine as a function of altitude at a ram pressure ratio of 1.2. At the 550 pound per hour setting this investigation was conducted over an altitude range of 40,000 to 47,000 feet and at the 420 pound per hour setting, over an altitude range of 45,000 to 51,000 feet.

Transient data. - Transient data were taken by manually advancing or cutting back the power lever in a stepwise manner. Engine parameters were measured continuously on oscillograph recorders. Before and after each transient, photographs of panel meters and manometers were taken to calibrate the transient traces. Steps of various sizes were made at altitudes of 10,000, 25,000, and 35,000 feet at a ram pressure ratio of 1.2. These tests were also performed for three minimum fuel flow settings of 550, 420, and 350 pounds per hour.

RESULTS

Effect of Limits on Operating Schedule

Actual values of speed and temperature obtained during operation with the different values of minimum fuel flow settings will be termed the "operating schedule" to distinguish them from the required or "reference schedule" of speed and temperature set into the control.

To illustrate the effects of limits on any reference schedule of speed and temperature, figure 3 is presented to show actual values of operating schedule along with curves of exhaust nozzle position, fuel valve position, fuel flow, and thrust as functions of power lever position when operating at a ram pressure ratio of 1.2 and altitudes of 10,000, 25,000, 35,000, and 45,000 feet.

In all cases, as long as the two inputs fuel flow and area are continuously variable, the control system maintains set values regardless of minimum fuel flow settings. For a large portion of the power lever range, however, either the fuel valve or exhaust nozzle or both are against a mechanical limit or stop. If one input variable is against a limit, then either speed or temperature or both will deviate from the set values. If both input variables are at limits, then both speed and temperature will depart from the set quantities to whatever values result
2409 from the limited values of area and fuel flow and the flight condition.

In view of the fact that the operating schedule of speed and temperature deviates in certain ranges of operation from the reference schedule with changes in flight conditions, the resulting operating thrust schedule will change accordingly. The reasons for these deviations can be found by referring to other parameters.

Figure 3(a) shows that at 10,000 feet of altitude and a ram pressure ratio of 1.2 the system operates in accordance with the reference schedule for all throttle settings above 62° with the 550 pound per hour setting of minimum fuel flow.

Below a power lever position of 62° the exhaust nozzle is wide open. Because the control is able to proportion only the fuel flow signal in this range, at least one of the outputs will be off the reference schedule. By use of the electronic limiting circuits in the control and proper proportioning of the gains in the various control loops, this system was made to control speed rather closely, thus causing temperature to rise above the set value. The actual temperature curve starts to break away from the reference schedule at the time the exhaust nozzle reaches its wide open limit. From 62° down to idle the engine operates as a fixed-area turbojet and the temperature obtained is whatever value results from the fuel flow needed to maintain speed at this flight condition.

At approximately 29° the fuel valve is against its minimum stop for this setting. Below 29°, both area and fuel flow are at limits and therefore both temperature and speed are off the set values. All parameters will remain constant at whatever values result from the wide-open-area position, the minimum fuel flow setting, and the selected flight condition.

Figure 3(a) also presents several points for the 350 pound per hour setting which in this case was low enough that the fuel valve did not hit its stop during steady-state operation. For this setting the speed levels off close to the set value, and the engine is still being controlled by fuel flow.

In figure 3(b), which is for an altitude of 25,000 feet and a ram pressure ratio of 1.2, it can be seen that at the higher power lever positions the general trend of the curves is much the same as for 10,000 feet. The exhaust nozzle is just at the wide open position when the throttle is retracted to approximately 65°. The nozzle does not stay fully open at low power lever positions for the 550 pound per hour minimum fuel flow setting, however, as it does for the 420 and 350 pound per hour settings. At about 34° the fuel valve hits the 550 pound per hour stop. As the lever is retracted to lower positions, the speed error overrides the temperature error and closes the nozzle to maintain required speed. Temperature rises sharply as the area closes, thus departing from the set values while speed deviates only a small amount until the area reaches the fully closed limit. Below 31° both the exhaust nozzle and the fuel valve are at limits and all variables are constant for this flight condition.

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It appears that the fuel valve has reached the 420 pound per hour stop at just about the same time as the idle flat spot is reached, and that the valve has not yet reached the stop for the 350 pound per hour setting because speed levels off at about 5000 rpm, which is approximately the set value. For these lower settings of the fuel valve, the temperature levels off at a lower value at the idle flat spot.

Thrust data shown on figure 3(b) indicate a more significant deviation from design schedule than those shown on figure 3(a) for conditions at 10,000 feet altitude. At low power lever positions, the thrust for a minimum fuel flow of 550 pounds per hour increases as the power lever is retarded and levels off at a relatively higher idle value. This higher idle thrust is due to the increase in temperature caused by area closure. For a minimum fuel flow setting of 420 pounds per hour, the thrust behaves in the same manner as at 10,000 feet, since the rise of temperature at low power lever positions does not occur. When the fuel valve is beyond the next higher minimum setting, the variables for both settings will be the same. As a result all curves shown should be valid for all minimum flow settings for throttle positions above 34°, which was the critical position for the 550 pound per hour setting.

In figure 3(c) for an altitude of 35,000 feet and a ram pressure ratio of 1.2, the effect of the fuel valve stop is even more evident. The fuel valve is against a stop below 41° on the power lever. As the power lever is retracted a few degrees below the point at which the fuel valve hits its stop, the nozzle closes to control speed. Because the nozzle closes at a higher engine speed for this altitude, the effect of the exhaust nozzle area on temperature is greater and temperature rises much more than at lower altitudes.

The thrust at 35,000 feet again exhibits a nonlinear variation with power lever travel. For operation with the 550 pound per hour setting, the data show that a relatively high idle thrust is obtained and that as the power lever is advanced, the thrust actually decreases before rising in the expected manner. Data obtained with the 420 pound per hour setting indicate a similar trend but with a lower idle thrust. The reason for this is again the high temperatures which occur at low power lever positions. The data for the lowest setting of 350 pounds per hour showed no rise in thrust at idle speed.

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Figure 3(d) presents data obtained at 45,000 feet and a ram pressure ratio of 1.2. No data are shown in this figure for the 550 pound per hour setting because the fuel valve was against its minimum stop during practically all the operation and the system response was very oscillatory. With the fuel valve stop set at 420 pounds per hour, however, the power lever range was increased, and when area was the controlling variable, the amplitude of oscillation was less.

Reference to the figure shows that the fuel valve is on the stop below 70° on the power lever. Also, the nozzle never reaches its wide open stop at this altitude and ram pressure ratio. Although the fuel valve is on a stop, the fuel flow decreases somewhat with decreasing engine speed. As a result, engine speed decreases in the range from 71° to 43° while the area is essentially constant. At 43° the nozzle starts to close and becomes fully closed at about 36°. Temperature increases drastically in this range until at 36° it is 1300°. Thus, it can be seen that damage to the engine due to overtemperature can result from operation in this region. At 36°, the exhaust nozzle is closed and the fuel valve is on a stop; therefore all variables are constant for all power lever positions below this value.

For the 550 pound per hour setting, as the power lever was retracted toward idle, the overtemperature condition was reached at a higher lever position and engine speed. Because the critical temperature conditions were reached with the area not fully closed, operation at lower positions was not possible because of the overtemperature condition that would result from further closing of the exhaust nozzle. Safe operation was possible over only a small range at the high end of the power lever quadrant.

Effect of Altitude on Safe Operating Range

The range of power lever position for safe engine operation at any altitude is shown in figure 4 for a minimum fuel flow setting of 550 pounds per hour and a ram pressure ratio of 1.2. Below 40,000 feet the engine will operate safely at all power lever positions.

Above 40,000 feet operation at the lower positions will result in excessive temperatures. If the power lever is retracted into the lower region the exhaust nozzle will close further to maintain speed and the temperature will rise. The power lever must be advanced as altitude is increased to keep the engine out of this region. Furthermore, as the power lever is advanced to prevent overtemperature and the altitude is increased, a point is reached at which the engine speed becomes excessive. This point is at a power lever position of 65° and an altitude of 46,500 feet. Additional information presented in this figure consists of the regions in which both the exhaust nozzle and fuel valve are controlling, the region in which only the fuel valve is controlling, the region in which only the exhaust nozzle is controlling, and the region in which neither is controlling. 2409

The small region of no control between that of control by exhaust nozzle area alone and that of control by fuel flow alone represents a condition where the fuel valve is just on its minimum stop and the exhaust nozzle is fully open. This region exists because speed is fairly close to schedule and the speed error is too small to overcome the limited value of temperature error which keeps the exhaust nozzle open. As the power lever is retracted, speed error increases and finally overcomes the effect of temperature error and gains control of the exhaust nozzle.

Figure 5 shows the increased range obtained by reducing the minimum setting to 420 pounds per hour. With this lower setting the altitude for safe operation over complete throttle range is increased from 40,000 to 45,000 feet. The maximum altitude is increased from 46,500 feet obtained with the 550 pound per hour setting to approximately 53,000 feet, which was obtained with the 420 pound per hour setting.

Effect of Minimum Fuel Flow Settings on Transient Performance

Reduced minimum fuel flow settings cause idle speed and idle temperature to be lower at any given altitude. It is expected, then, that accelerations, decelerations, burner blow-out, and stall will be influenced when accelerating from or decelerating to the lower engine speeds. Figure 6, illustrating the transient performance, is presented in the form of reproductions of oscillographic traces which have been reduced to 71 percent of their original size. The following parameters are shown: thrust, compressor discharge pressure, exhaust nozzle area, engine speed, turbine discharge temperature, primary fuel valve position, and throttle position.

Calibration data are included on each trace except that of thrust. Variations in ram pressure during the transient were found to influence the thrust trace, making calibration questionable.

The oscillograph traces of the transient data are indexed in table II according to altitude, ram pressure ratio, minimum fuel flow setting, and throttle position. The figures chosen are representative of the operation of the controlled engine within the range of throttle settings from idle (26°) to full military (82°) and show effect of the minimum fuel flow setting on accelerations, decelerations, blow-out, and stall. Table III summarizes the transient runs to facilitate the comparison of minimum fuel flow effects.

Acceleration and deceleration time. - Gas turbine engines have the characteristic of accelerating slowly at low engine speeds. Reduced fuel valve settings result in lower idle speeds and therefore slower accelerations from idle. The longer acceleration time for the lower settings is illustrated by comparing figures 6(a) and 6(b) for the 550 and 350 pound per hour settings, respectively. These figures are for an altitude of 10,000 feet and a ram pressure ratio of 1.2. The time for speed to reach approximately its final value after a sudden increase in throttle position from idle was 4 seconds for the 550 pound per hour setting in comparison with 6.5 seconds for the lower setting. The slower acceleration is reflected in the other traces that are affected by speed. The general shapes of the curves for both settings, however, are similar.

The same general trend of slower accelerations at lower fuel valve settings is indicated in figures 6(e), 6(f), and 6(g) for the 550, 420, and 350 settings, respectively, at an altitude of 25,000 feet. The corresponding times for speed to reach the final value are 4.8, 6, and 8.4 seconds.

When accelerating from the same initial speed, the response time will be approximately the same for any setting of the fuel valve. This is illustrated by figures 6(l) and 6(m), which are accelerations from approximately the same speed at 35,000 feet and fuel flow settings of 550 and 420 pounds per hour. Generally, the deceleration time is affected very little by changes in fuel valve setting. When the setting is lowered sufficiently, however, idle speed can approach the engine windmilling speed and for these cases the deceleration time is appreciably longer.

Figures 6(c) and 6(d) illustrate that at 10,000 feet and a ram pressure ratio of 1.2 the deceleration times from maximum speed to idle were very nearly the same for minimum fuel flow settings of 550 and 350 pounds per hour. Similar maximum step decelerations at 25,000 feet of altitude shown in figures 6(h), 6(i), and 6(j) indicate that the deceleration time again is about the same for the 550 and 420 settings, whereas that for the 350 setting is appreciably longer. The longer deceleration time for

the latter case is attributed to the windmilling effect of ram pressure on the engine.

Blow-out. - Another characteristic of gas turbine engines is the susceptibility to burner blow-out at low values of engine speed. Reduced fuel valve settings and the resulting lower idle speeds increase the possibilities for blow-out. The tendency toward blow-out is illustrated in figure 6(k) for 25,000 feet of altitude and a setting of 420 pounds per hour. The throttle was advanced rapidly from 32° (6700 engine rpm) 2409
to full military speed and a normal acceleration resulted. The engine was then decelerated to idle speed, which was 5000 engine rpm. When the throttle was again advanced, the engine would not accelerate. It appeared that although a complete blow-out did not occur, combustion was taking place behind the turbine as a result of engine operation approaching the blow-out limit.

Figures 6(n) and 6(o) show a similar action at 35,000 feet of altitude for the 420 pound per hour minimum fuel flow setting. In the first case, for a step from idle to full military speed, there was a long hesitation and erratic action but the engine finally accelerated. For the latter case, however, the engine would not accelerate and after a few seconds blow-out occurred.

On deceleration, no blow-outs were encountered. Figure 6(j) shows a deceleration for 25,000 feet of altitude and a fuel valve setting of 350, and figure 6(p), for 35,000 feet of altitude and a fuel valve setting of 420. These represent the most likely conditions for blow-out on deceleration for which data are available.

It is seen, then, that reduced fuel valve settings, by causing lower idle speeds, aggravate the blow-out problem on accelerations from these low speeds, but in the range of flight conditions investigated lower settings do not cause blow-out during decelerations.

Stall. - Lower minimum fuel flow settings were shown to cause lower idle speeds and slower accelerations. At the beginning of an acceleration, fuel flow increases quickly and the compressor pressure ratio can exceed the surge limit. Reduced fuel valve settings, lower idle speeds, and slower accelerations cause the compressor to begin surging during accelerations at lower engine speeds. Steps from idle to full military speed are shown in figures 6(e), 6(f), and 6(g) for the 550, 420, and 350 pound per hour settings at an altitude of 25,000 feet. These figures indicate surging in each case. The characteristics of this engine are such that satisfactory accelerations were feasible even though the compressor was surging.

DISCUSSION

Problems Associated with Engine and Control Limits

2409 The results of this investigation show that several problems associated with steady-state operation are caused by engine and control limits. Large deviations from the reference schedule which occurred were primarily due to fuel valve and exhaust nozzle stops. The fact that deviations occur is not in itself objectionable. In fact, one of the purposes of the minimum fuel valve stop was to cause engine speed to deviate above the reference speed as altitude increased. As altitude increased, however, these limits resulted in such undesirable effects as (1) deviations of temperature from the set value at low power lever positions to the extent that unsafe values were obtained; (2) a nonlinear relation of thrust to power lever position, which in some cases resulted in a higher thrust at idle than at higher power lever position; (3) a limit on the maximum altitude for safe operation; and (4) a condition at which the maximum altitude for safe operation varied with the power lever position and was less at low power than at high.

Effect of Lowering Minimum Fuel Valve Stop

One method of alleviating the undesirable or dangerous conditions that arise is to lower the minimum fuel valve stop. When the range of the fuel valve is increased, more complete control is obtained, and as a result of the smaller deviation of temperature and speed from the reference values, thrust will be a more linear function of throttle position. Also, a lower idle thrust is available for maneuvering and descending from high altitude, and the range of altitudes for safe operation has been increased.

The only serious problem with regard to transient operation which appears to arise as a result of a lower minimum fuel flow setting is an increased tendency for engine blow-out on accelerations. This problem could be eliminated by the addition of a control device designed specifically to prevent blow-outs during transients.

The conclusion is that lowering the minimum fuel flow setting will improve the steady-state engine performance over a wider range, but that satisfactory transient performance necessitates the addition of blow-out protection. If the requirements in flight conflict with those for ground starting, a separate starting schedule is also necessary.

Overtemperature Signal to

Exhaust Nozzle Servo

Another method of alleviating some of the difficulties is to provide an overtemperature signal to the exhaust nozzle servo. If an overtemperature signal were added to the exhaust nozzle control as well as to the fuel control, excessive temperatures at low power lever positions could be avoided. A dangerous situation could thus be eliminated and at the same time the maximum altitude for safe operation would be the same for both high and low power settings. Such a device would remove the unexpected rise in temperature to unsafe values that occurs in the existing system when the power lever is retracted to idle at high altitude. This device would not remove the thrust reversal with throttle position nor cause a more linear variation, nor would it raise the maximum altitude for safe operation at high power lever positions. The device could also be used in conjunction with a lower fuel valve setting and the benefits of both changes could thus be obtained.

Varying Reference Speed

with Altitude

A better method providing suitable idle speeds at altitude is to vary the idle end of the reference schedule with altitude or total inlet pressure. The minimum fuel flow setting then could be lowered to a value determined by deceleration blow-out. Inasmuch as no trouble was experienced with lean blow-out in this investigation even with the lowest minimum fuel flow setting, this problem does not appear too serious. Specific protection against the occurrence of deceleration blow-out, however, could be added in the form of a variable limit on fuel valve closure instead of the fixed minimum valve stop.

These changes would remove the overtemperature problem that arises at low power lever positions as a result of closure of the exhaust nozzle in an attempt to maintain a reference speed. At the same time the low power ceiling would be increased. Also, by eliminating the need for a high fuel valve setting, the maximum altitude for safe operation at any power lever position can be increased. Furthermore, removing the cause of closed nozzle operation at low power would eliminate the thrust reversal and give a more linear variation of thrust with power lever position. If the set speed is varied with altitude in a manner that gives approximately the same idle speeds as are now obtained with the 550 pound per hour minimum fuel valve setting, the transient performance should be comparable to that for the 550 setting. It appears that practically all the difficulties that existed during steady-state operation with the 550 pound per hour setting could be eliminated while

similar transient performance is maintained. Similarly, if the reference speed were increased with altitude according to the relation that exists for the 420 or 350 setting, transient performance similar to that for the respective setting should result. If specific blow-out protection is provided, lower idle thrust can be obtained than with the other systems discussed.

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CONCLUDING REMARKS

The use of a fixed minimum fuel flow in the engine control simplifies the control by preventing combustion blow-out and eliminating the need for special fuel flow settings for starting. The advantages of this simplicity are offset by performance penalties. These penalties are the limitations of a maximum altitude above which the engine cannot operate without overtemperature or overspeed and a distortion of the thrust schedule at altitude to the extent that retarding the power lever can result in increased thrust, accompanied by possible overheating of the turbine. Also, the range of thrust modulation available is restricted at high altitude. Although difficulties may not exist in applications to some aircraft at present, as present and future aircraft operate at higher altitudes, some means of avoiding the problems should be considered.

Possible actions to overcome these difficulties are a more judicious choice of minimum fuel flow and the incorporation of additional control components to provide protection from blow-out without the need for a fixed minimum fuel flow. Experiments with low minimum fuel flow showed an alleviation of the difficulties discussed, but increased the occurrence of acceleration blow-out. Therefore, this means of avoiding the minimum fuel flow difficulties is not satisfactory unless a protective device is provided with an action more specifically a function of blow-out.

A better solution to the problem would be to vary the idle end of the reference speed schedule with total inlet pressure. With this system, acceleration blow-out could be avoided without adversely affecting steady-state performance. The minimum fuel flow need be set only high enough to avoid deceleration blow-out.

Lewis Flight Propulsion Laboratory
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APPENDIX - SYMBOLS

The following symbols are used in this report:

N	engine speed
N_s	set speed
N_e	speed error 2409
$\overline{N_e}$	speed error limited in positive direction
T	turbine discharge temperature
$\underline{T}$	temperature signal limited below full military value
T_s	set temperature
T_e	temperature error
$\overline{\underline{T_e}}$	temperature error limited in both positive and negative directions
W_f	fuel flow
$\overline{\underline{W_f}}$	fuel flow limited in maximum and minimum directions
A	exhaust nozzle area
$\overline{\underline{A}}$	exhaust nozzle area limited in maximum and minimum directions
I	input
O	output
K_1, K_2, K_3, K_4, and K_5	constants

REFERENCE

1. Delio, Gene J., and Schwent, Glennon V.: Instrumentation for Recording Transient Performance of Gas-Turbine Engines and Control Systems. NACA RM E51D27, 1951.

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TABLE I - TABLE OF INSTRUMENTATION

Measured quantity	Steady-state instrumentation	Transient instrumentation	
		Sensor	Range over which frequency response is essentially flat (cycles/sec)
Compressor discharge pressure	Mercury-filled manometer	Aneroid-type pressure sensor with strain gage element	0-10 at sea-level pressure
Exhaust nozzle area	Microammeter connected to exhaust nozzle area feedback potentiometer	Exhaust nozzle area feedback potentiometer connected to give position indication	0-100
Engine speed	Chronometric tachometer	Direct current tachometer generator	0-5
Turbine discharge temperature	Nine thermocouples in parallel connected to Brown recorder (Westinghouse control thermocouple harness)	Unshielded loop thermocouples (five in series)	0-1 at sea-level mass flow
Primary fuel valve position	Microammeter connected to fuel valve feedback potentiometer	Fuel valve feedback potentiometer connected to give position indication	0-100
Thrust		Strain gage mounted on strain link attached to forward engine suspension	0-100
Throttle position	Selsyn indicator	Wire-wound potentiometer connected to give position indication	0-100

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TABLE II - INDEX OF TRANSIENT DATA

[Nominal ram pressure ratio, 1.2]

Figure number	Minimum fuel flow (lb/hr)	Initial power lever position (deg)	Final power lever position (deg)	Altitude (ft)
6(a)	550	22	84	10,000
6(b)	350	20.5	83	10,000
6(c)	550	84	22	10,000
6(d)	350	83	21	10,000
6(e)	550	20.5	83	25,000
6(f)	420	22	85	25,000
6(g)	350	22	84	25,000
6(h)	550	83	20.5	25,000
6(i)	420	85	22	25,000
6(j)	350	84	22	25,000
6(k)	420	32 to 85 to	20 to 85	25,000
6(l)	550	36.5	84	35,000
6(m)	420	39	84	35,000
6(n)	420	25	84	35,000
6(o)	420	25 to 84 to	cut-off	35,000
6(p)	420	84	25	35,000

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TABLE III - SUMMARY OF TRANSIENT PERFORMANCE

Altitude (ft)	Ram pressure ratio		Minimum fuel flow (set at 1500 rpm) (lb/hr)		
			550	[a]420	[b]350
10,000	1.2	Figure number	6(a)		6(b)
		Throttle step, deg	22 to 84		20.5 to 83
		Engine speed, rpm	5420 to 12,580		4900 to 12,530
		Remarks	4 sec for speed to get to final value (some overshoot)		6.5 sec for speed to reach final value. 2.5 sec longer than for 550
		Figure number	6(c)		6(d)
		Throttle step, deg	84 to 22		83 to 21
		Engine speed, rpm	12,580 to 5420		12,530 to 4960
		Remarks	Deceleration time same as for 350		Deceleration time same as for 550
25,000	1.2	Figure number	6(e)	6(f)	6(g)
		Throttle step, deg	20.5 to 83	22 to 85	22 to 84
		Engine speed, rpm	7280 to 12,520	5320 to 12,540	4870 to 12,530
		Remarks	4.8 sec for speed to reach final value	Engine accelerates slowly for first 2 sec. 6 sec for speed to reach final value.	Engine accelerates slowly for first 5 sec. 8.4 sec for speed to reach final value.
		Figure number	6(h)	6(i)	6(j)
		Throttle step, deg	83 to 20.5	85 to 22	84 to 22
		Engine speed, rpm	12,520 to 7280	12,540 to 5320	12,530 to 4870
		Remarks	Deceleration takes approximately 7 sec	Approximately 7 sec for deceleration. Same as for 550.	Approximately 11 sec for deceleration.
		Figure number		6(k)	
		Throttle step, deg		32 to 85 to 20 to 85	
		Engine speed, rpm		6700 to 12,540 to 5000 to -	
		Remarks		Engine would not accelerate on last step.	
35,000	1.2	Figure number	6(l)	6(m)	
		Throttle step, deg	36.5 to 84	39 to 84	
		Engine speed, rpm	9430 to 12,560	9160 to 12,540	
		Remarks	Went into stall once. Speed reached final value at approximately 4.5 sec	Went into stall 4 times causing oscillatory response. Speed reached final value in 4.5 sec	
		Figure number		6(n)	
		Throttle step, deg		25 to 84	
		Engine speed, rpm		6400 to 12,540	
		Remarks		Engine would not accelerate for 6 sec after step, then speed came up. Went into surge twice.	
		Figure number		6(o)	
		Throttle step, deg		25 to 84 to cut-off	
		Engine speed, rpm		6800 to ----	
		Remarks		Engine would not accelerate, then fire went out, then operator cut back.	
		Figure number		6(p)	
		Throttle step, deg		84 to 25	
		Engine speed, rpm		12,540 to 6800	
		Remarks		Idle speed much lower than for 550, giving lower idle thrust.	NACA

[a]420 lb/hr minimum fuel flow setting extends range of operation over 550. Will allow lower thrust for descent from altitude. Accelerations from low operating points are sluggish, however, and blow-out is encountered at 25,000 feet and above.

[b]350 lb/hr minimum fuel flow extends range of operation even further. Decelerations still seem to be all right. This setting will allow even lower idle thrust. Accelerations from low operating points are even more sluggish and susceptible to blow-out.

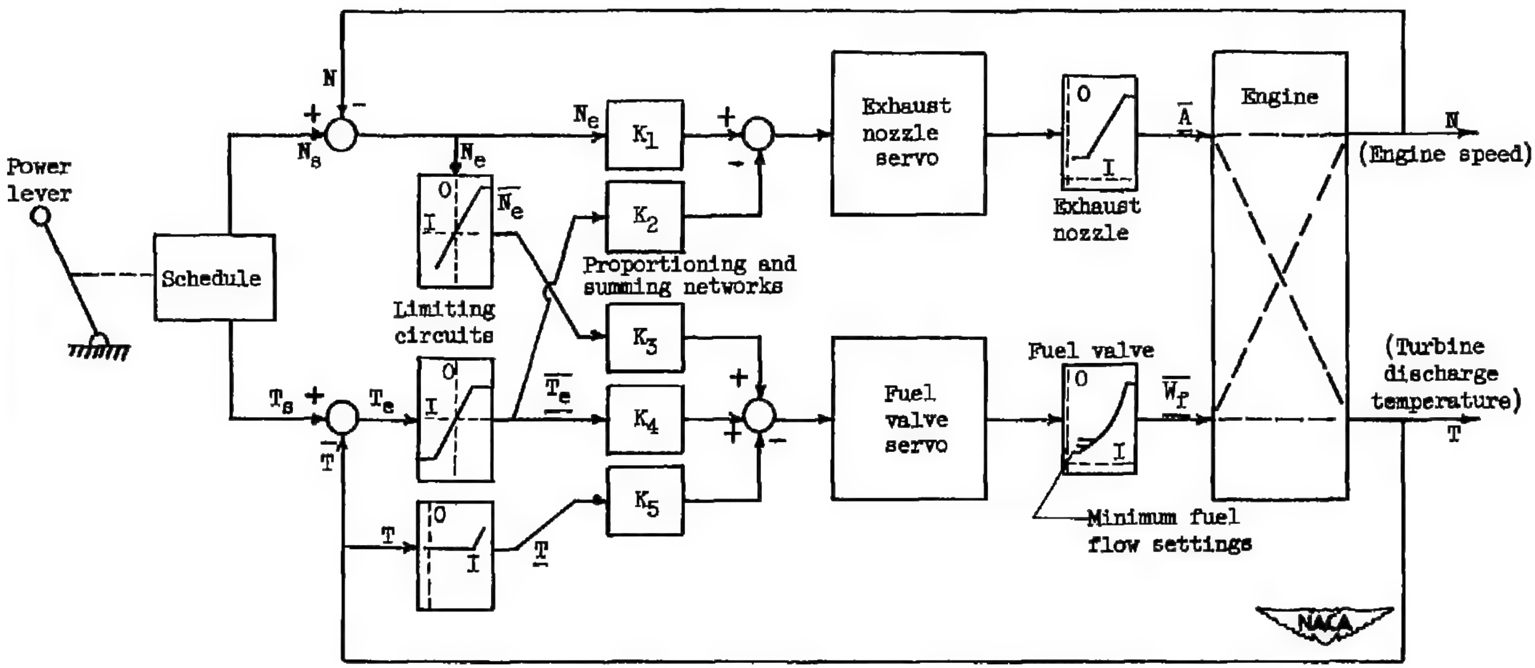


Figure 1. - Block diagram of Westinghouse J34-WE-32 primary control system.

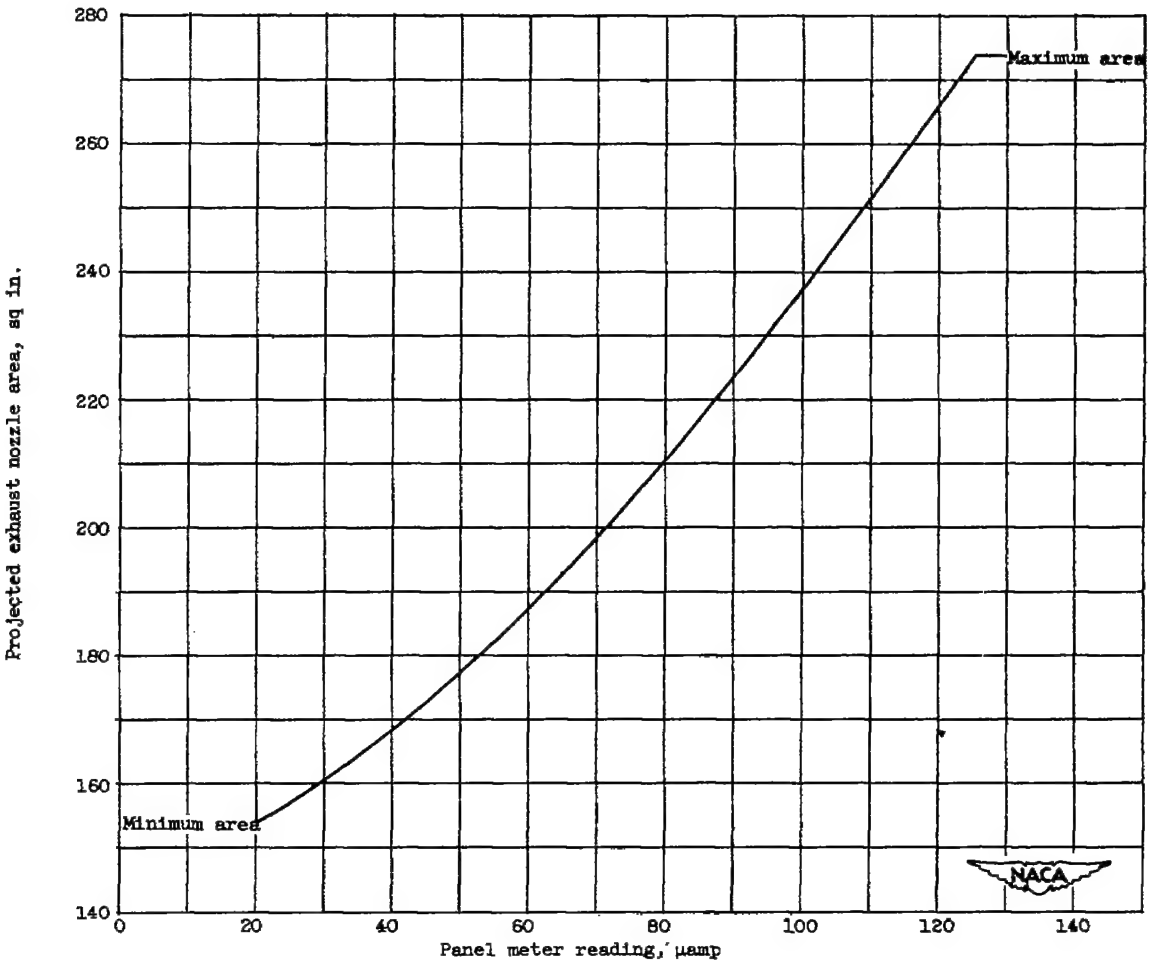
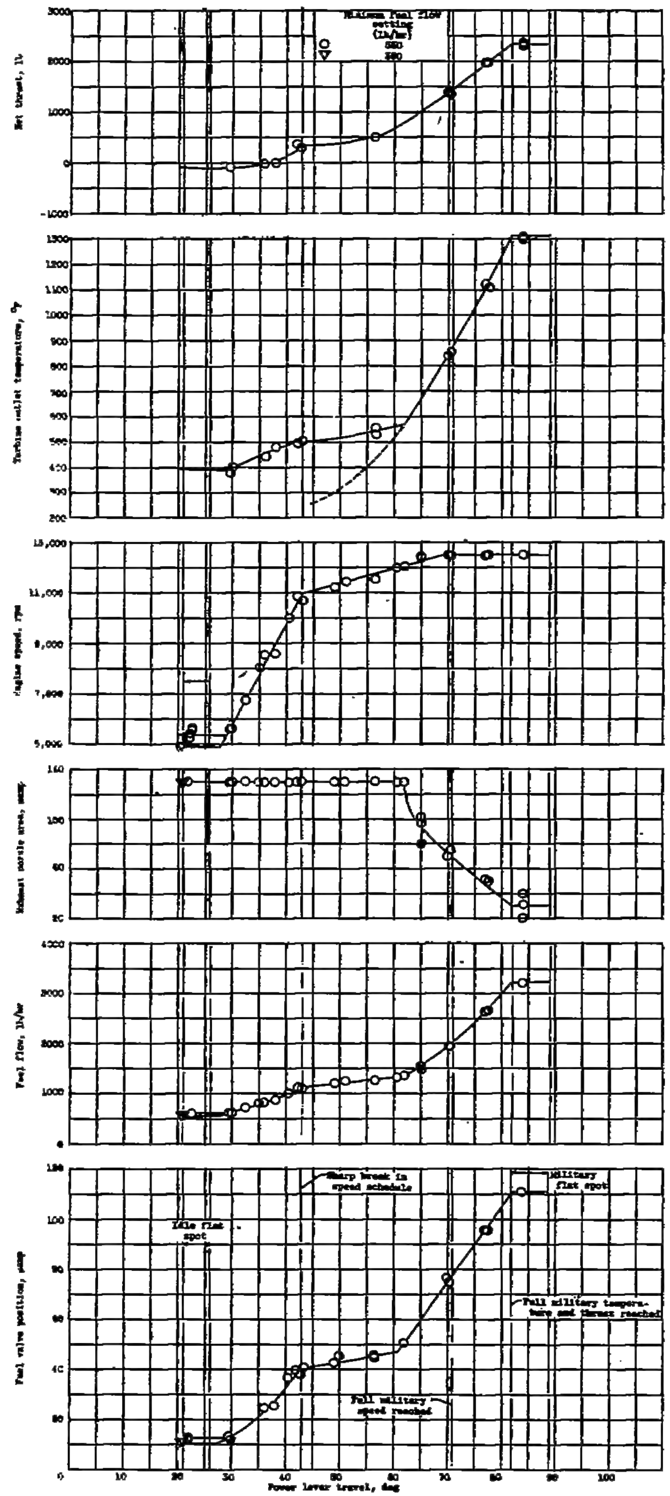


Figure 2. - Calibration of Westinghouse variable-area nozzle for J34-WE-32 turbojet engine.



(a) Altitude, 10,000 feet.

Figure 3. - Variation of net thrust, turbine outlet temperature, engine speed, exhaust nozzle area, fuel flow, and fuel valve position with power lever travel for different values of minimum fuel flow setting. Ram pressure ratio, 1.2.

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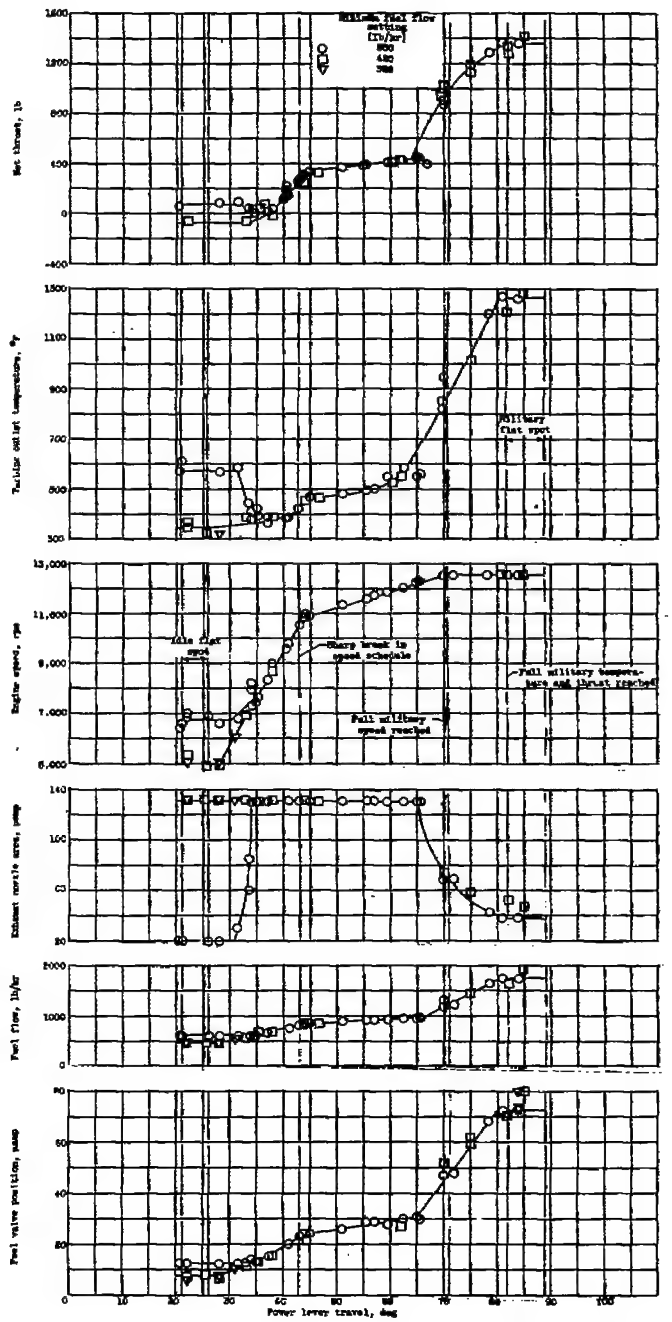

(b) Altitude, 25,000 feet.

Figure 3. - Continued. Variation of net thrust, turbine outlet temperature, engine speed, exhaust nozzle area, fuel flow, and fuel valve position with power lever travel for different values of minimum fuel flow setting. Ram pressure ratio, 1.2.

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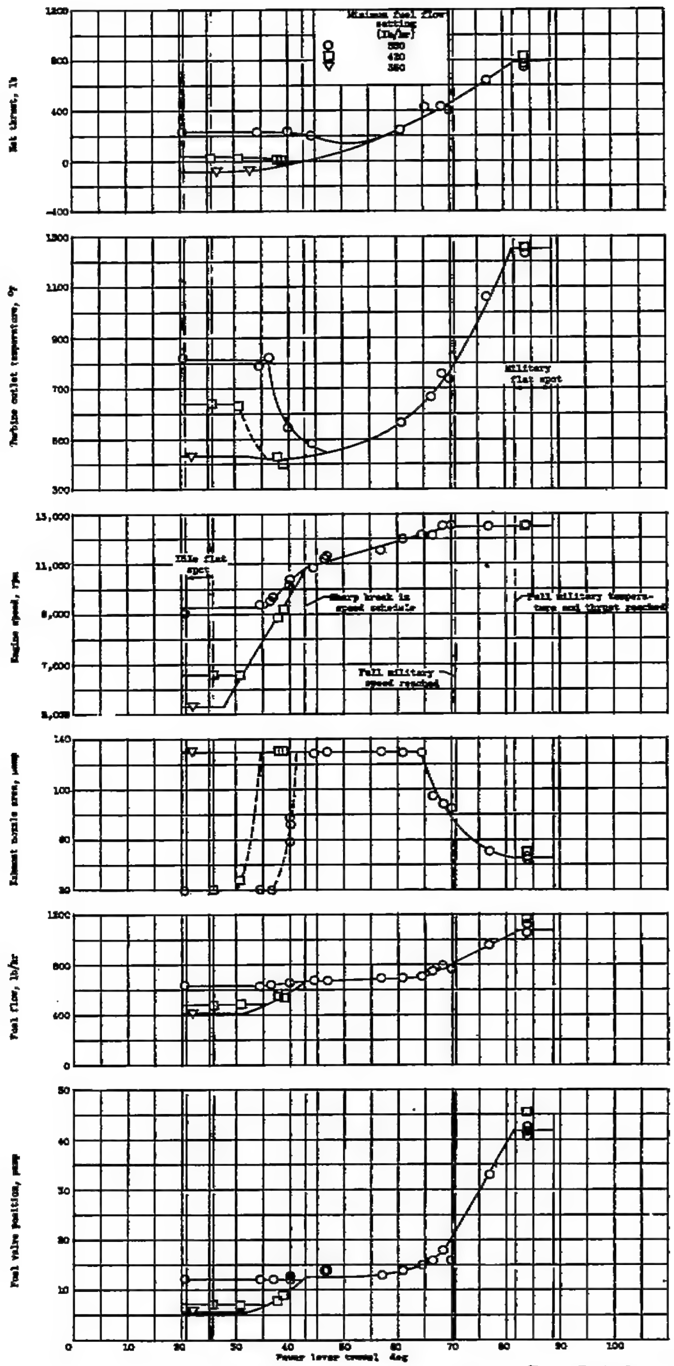

(c) Altitude, 35,000 feet.

Figure 3. - Continued. Variation of net thrust, turbine outlet temperature, engine speed, exhaust nozzle area, fuel flow, and fuel valve position with power lever travel for different values of minimum fuel flow setting. Ram pressure ratio, 1.2.

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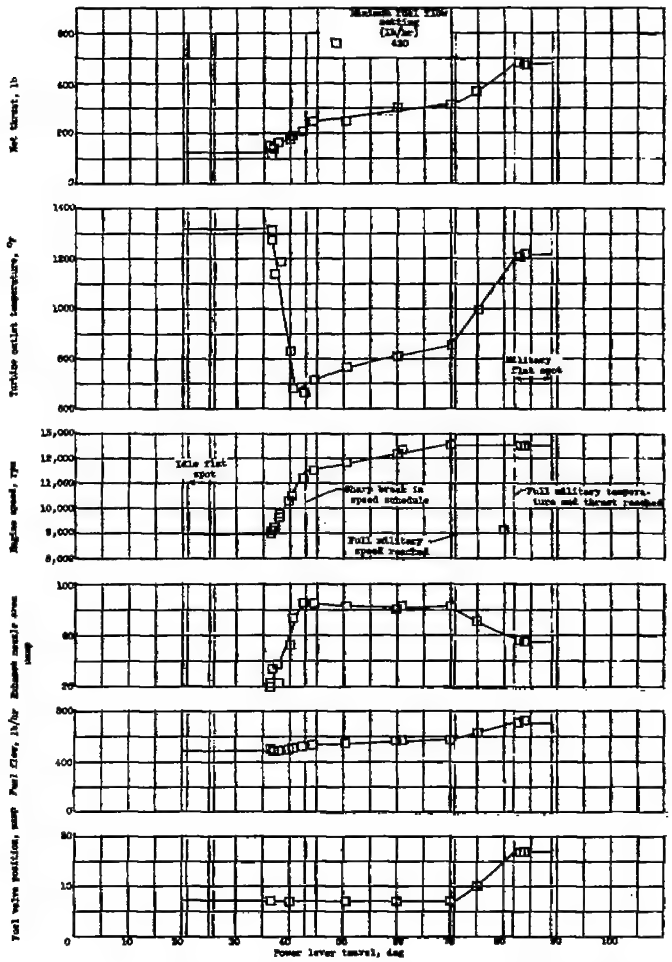

(d) Altitude, 45,000 feet.

Figure 3. - Concluded. Variation of net thrust, turbine outlet temperature, engine speed, exhaust nozzle area, fuel flow, and fuel valve position with power lever travel for different values of minimum fuel flow setting. Ram pressure ratio, 1.2.

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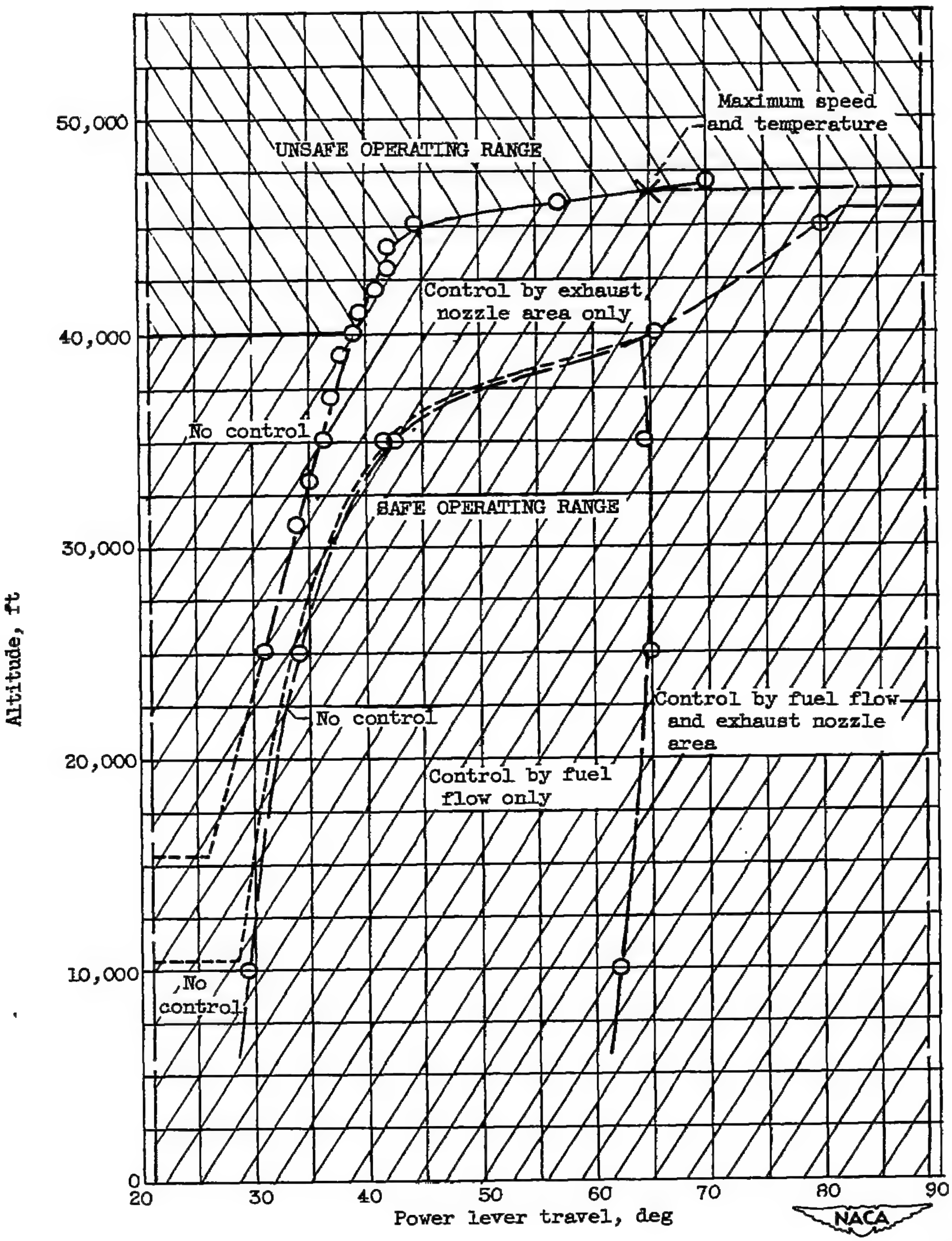

Figure 4. - Effect of altitude and power lever position on safe and unsafe operating ranges of controlled engine and on type of control existing in safe operating range. Minimum fuel flow, 550 pounds per hour; ram pressure ratio, 1.2.

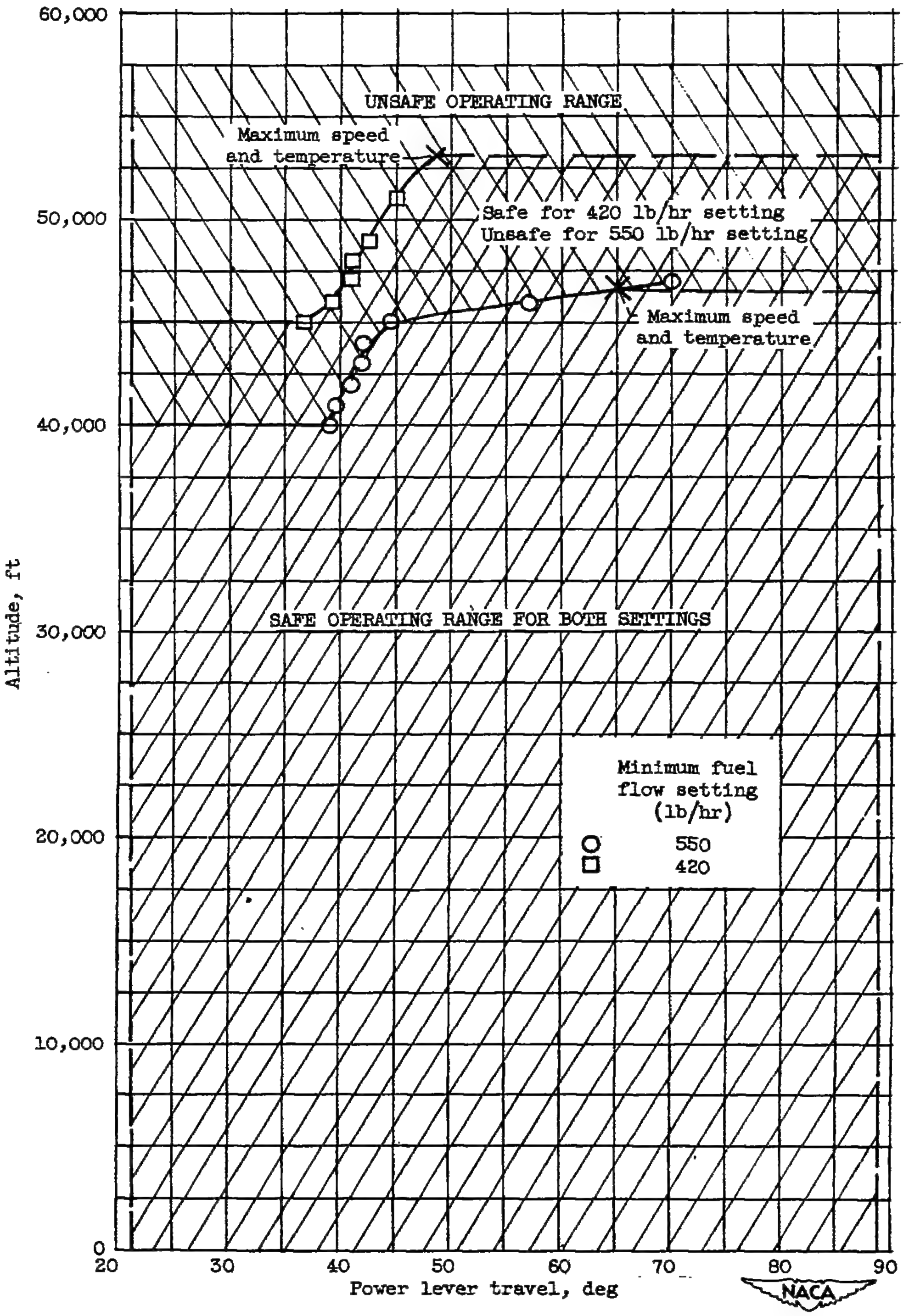

Figure 5. - Power lever travel for controlled engine showing safe and unsafe operating ranges as a function of altitude with different minimum fuel flow settings. Ram pressure ratio, 1.2.

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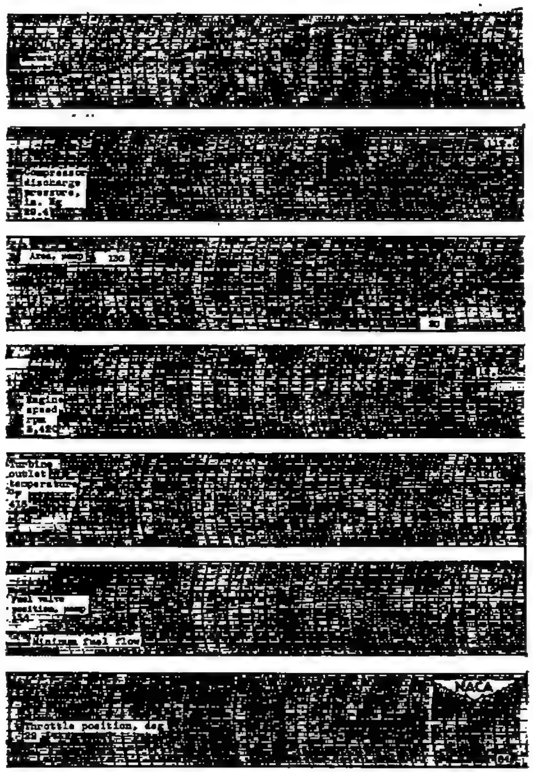

(a) Minimum fuel flow setting, 550 pounds per hour; power lever position, 22° to 84°; altitude, 10,000 feet.

Figure 6. - Transient operation of automatically controlled engine at a nominal ram pressure ratio of 1.2.

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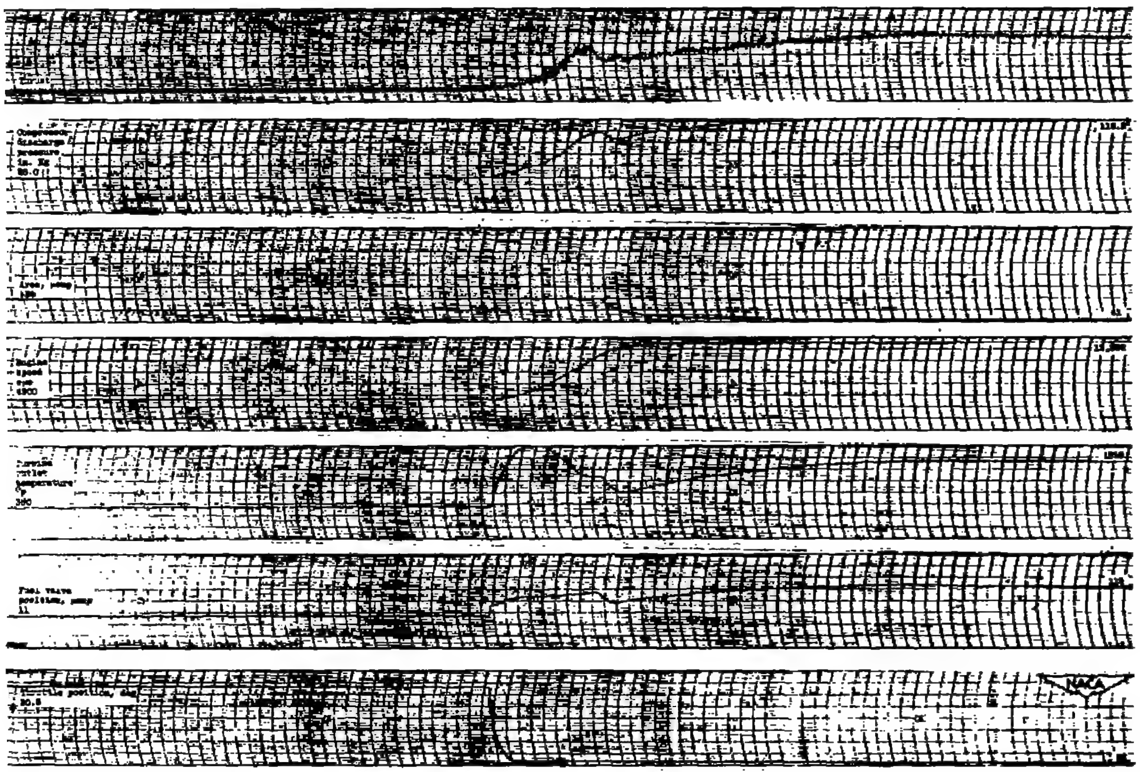
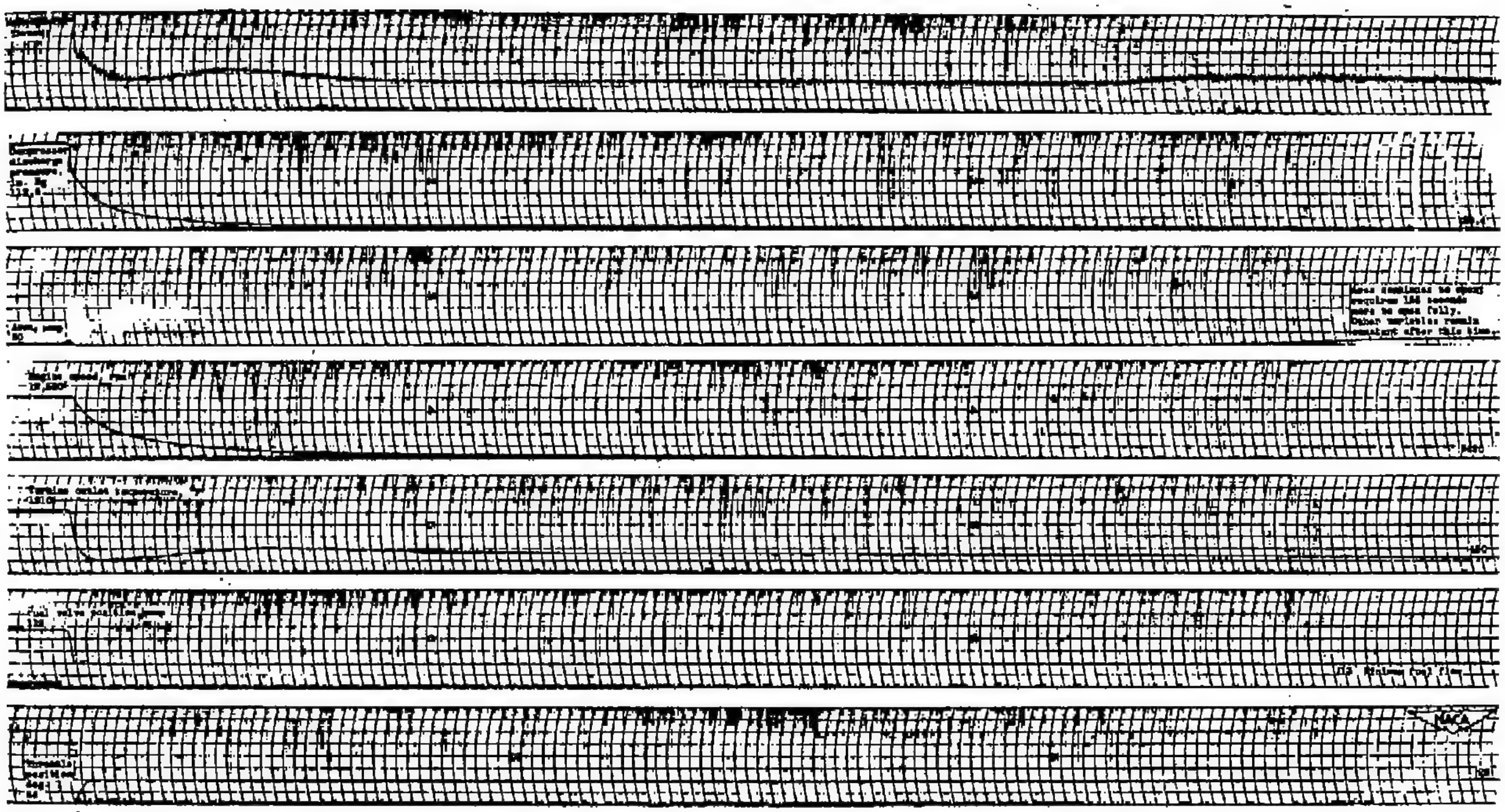


(b) Minimum fuel flow setting, 350 pounds per hour; power lever position, 20.5° to 83°; altitude, 10,000 feet.

Figure 6. - Continued. Transient operation of automatically controlled engine at a nominal ram pressure ratio of 1.2.



(c) Minimum fuel flow setting, 550 pounds per hour; power lever position, 84° to 22°; altitude, 10,000 feet.

Figure 6. - Continued. Transient operation of automatically controlled engine at a nominal ram pressure ratio of 1.2.

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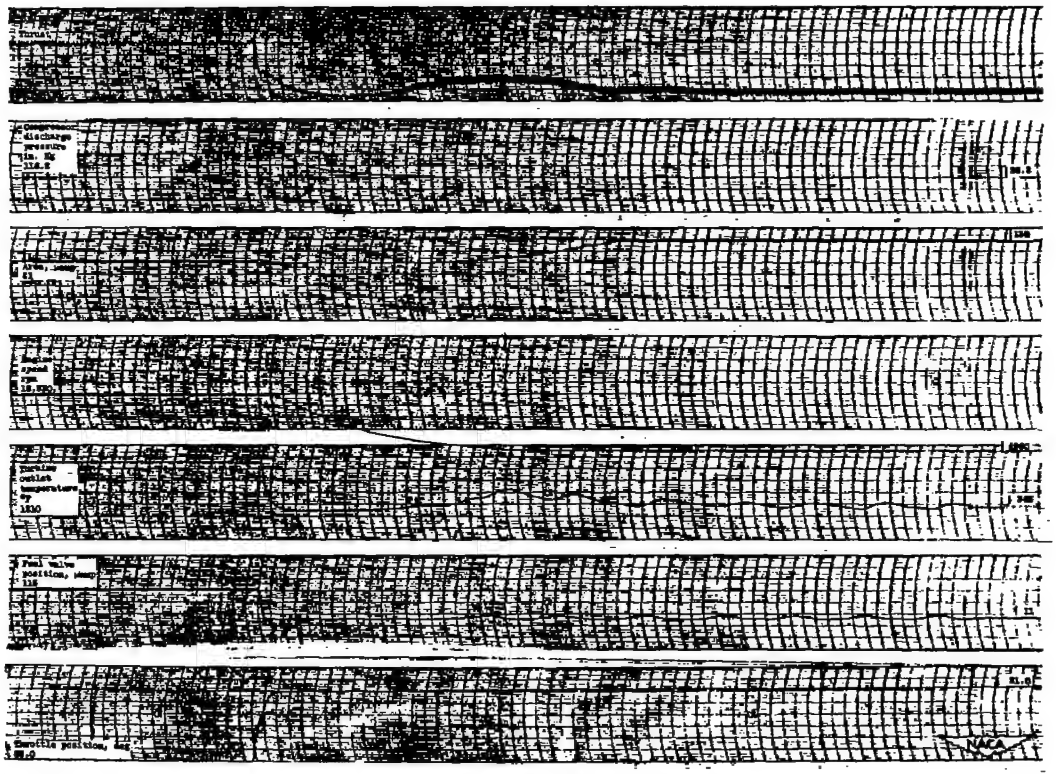
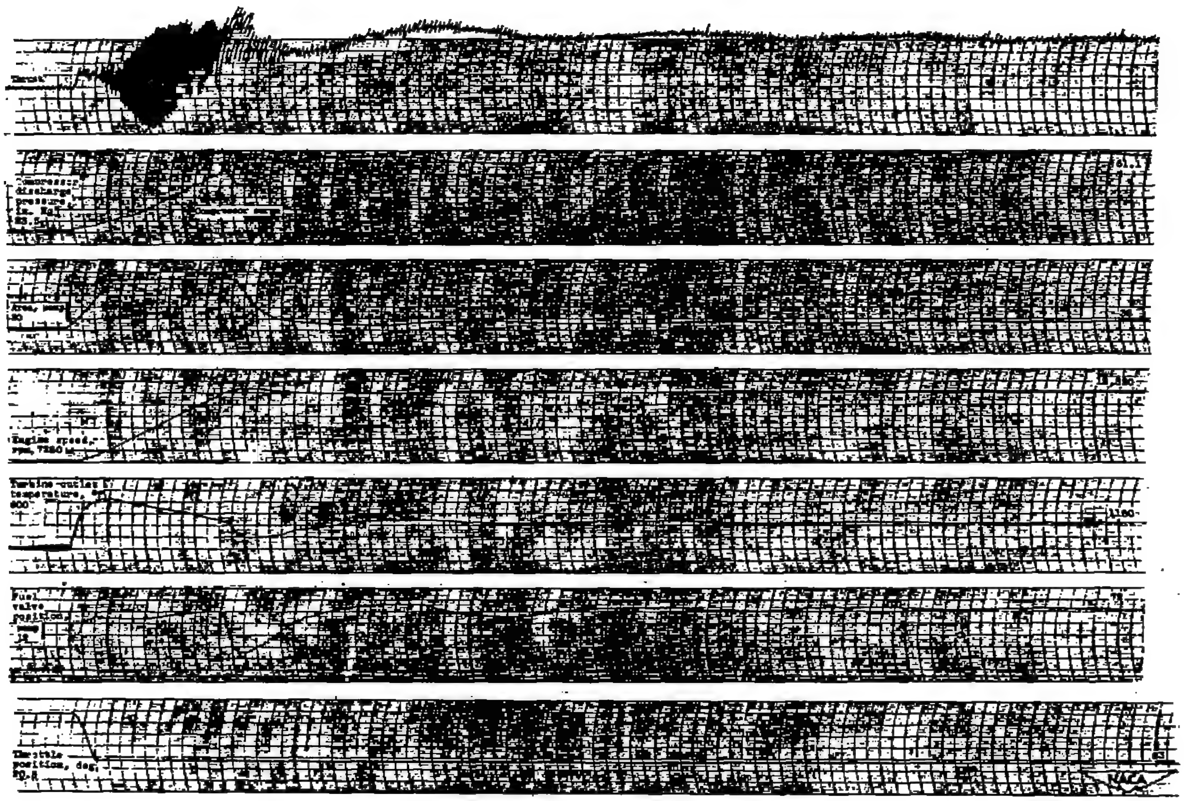


(d) Minimum fuel flow setting, 350 pounds per hour; power lever position, 83° to 21°; altitude, 10,000 feet.

Figure 6. - Continued. Transient operation of automatically controlled engine at a nominal ram pressure ratio of 1.2.



(e) Minimum fuel flow setting, 550 pounds per hour; power lever position, 20.5° to 83°; altitude, 25,000 feet.

Figure 6. - Continued. Transient operation of automatically controlled engine at a nominal ram pressure ratio of 1.2.

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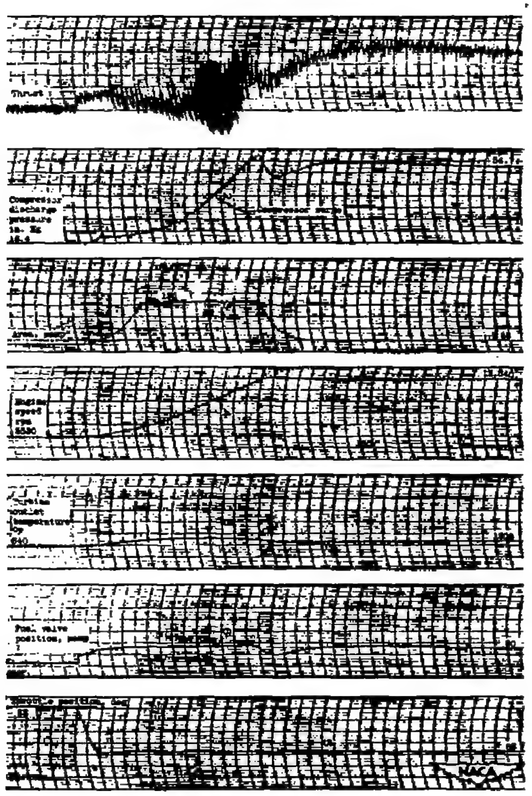

(f) Minimum fuel flow setting, 420 pounds per hour; power lever position, 22° to 85°; altitude, 25,000 feet.

Figure 6. - Continued. Transient operation of automatically controlled engine at a nominal ram pressure ratio of 1.2.

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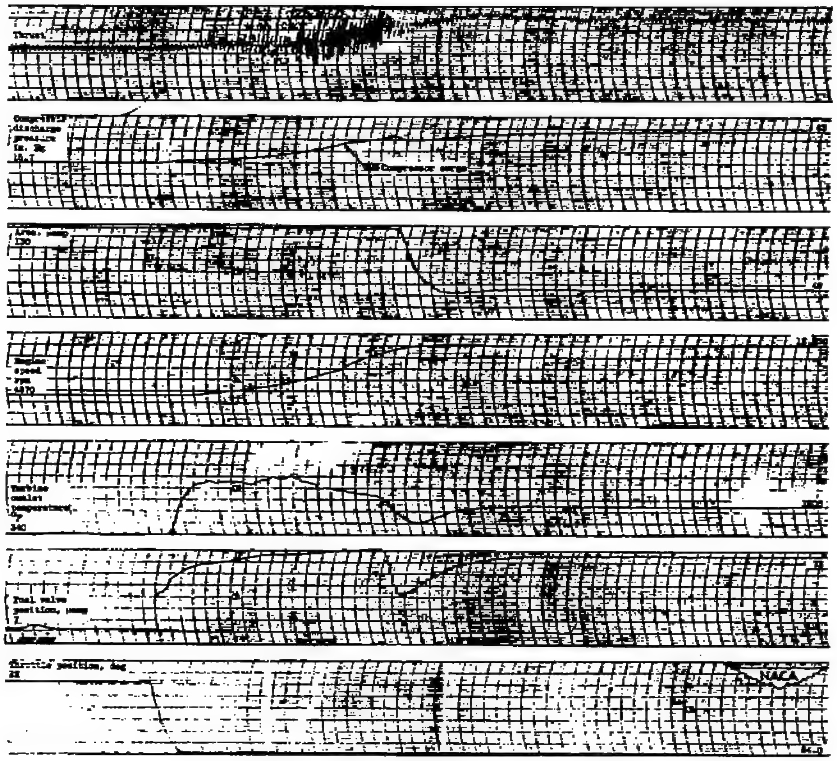

(g) Minimum fuel flow setting, 350 pounds per hour; power lever position, 22° to 84°; altitude, 25,000 feet.

Figure 6. - Continued. Transient operation of automatically controlled engine at a nominal ram pressure ratio of 1.2.

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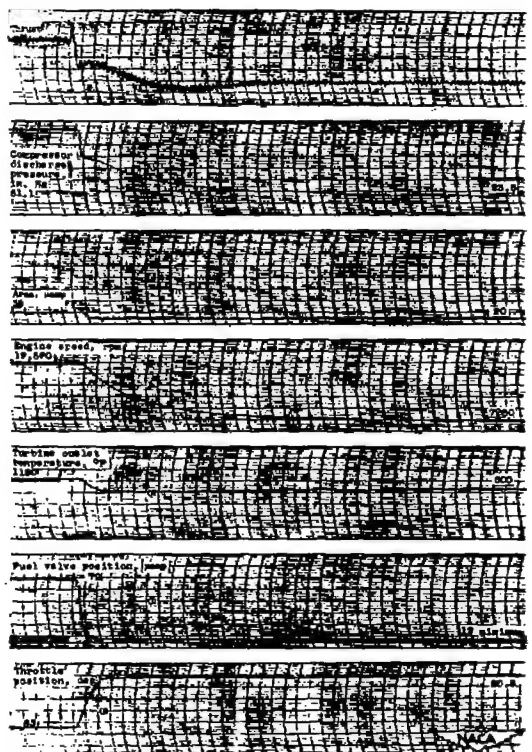

(b) Minimum fuel flow setting, 550 pounds per hour; power lever position, 83° to 20.5°; altitude, 25,000 feet.

Figure 6. - Continued. Transient operation of automatically controlled engine at a nominal ram pressure ratio of 1.2.

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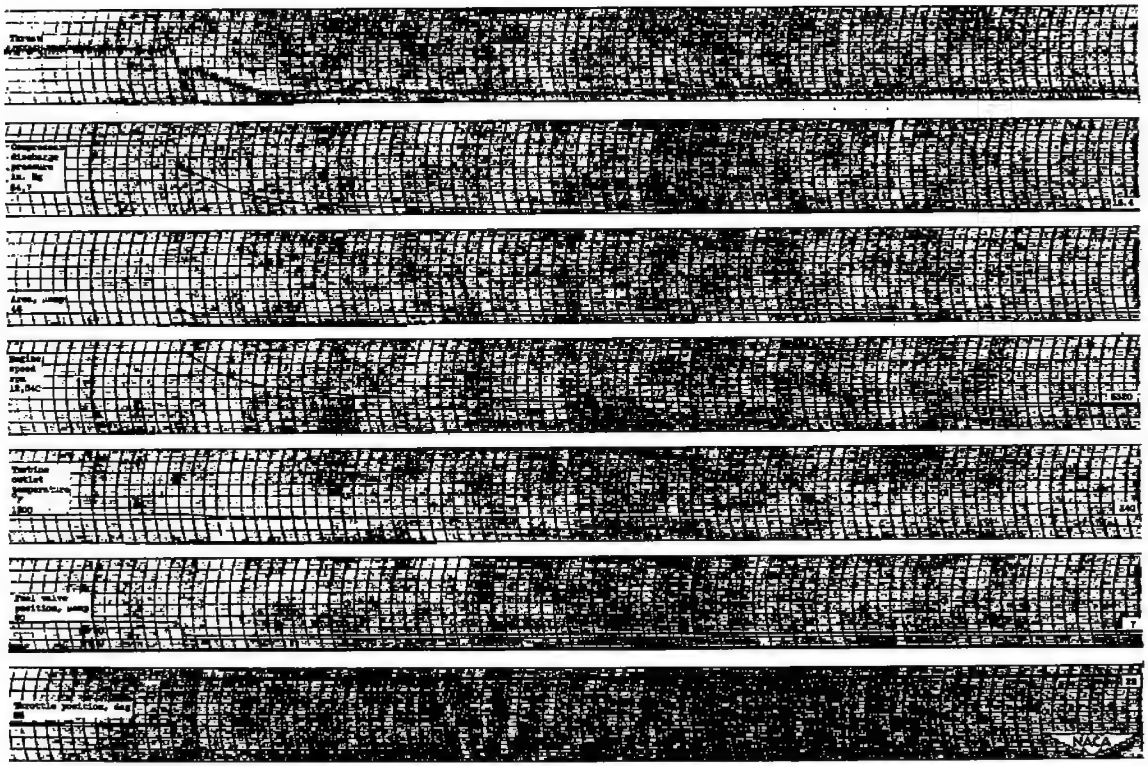
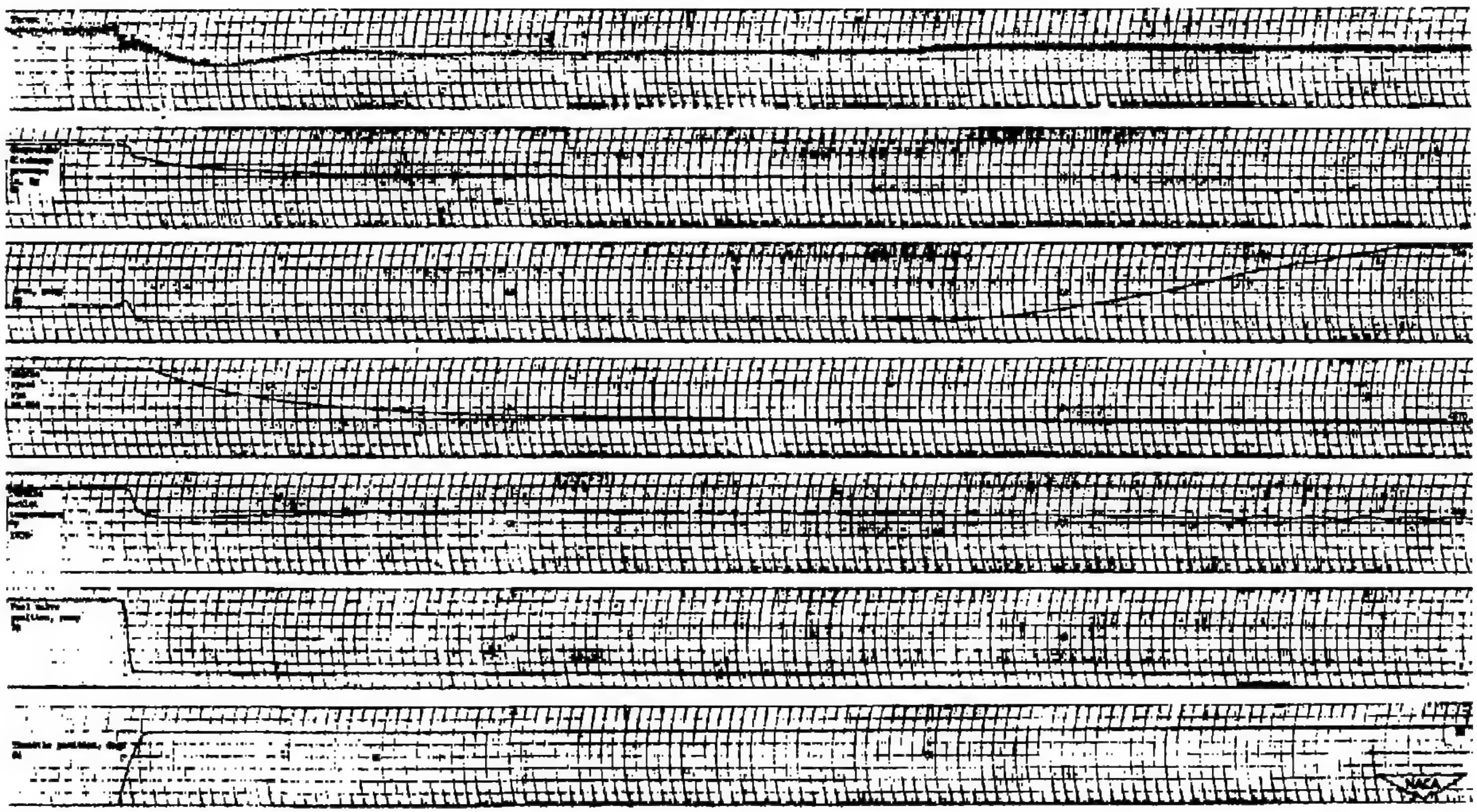


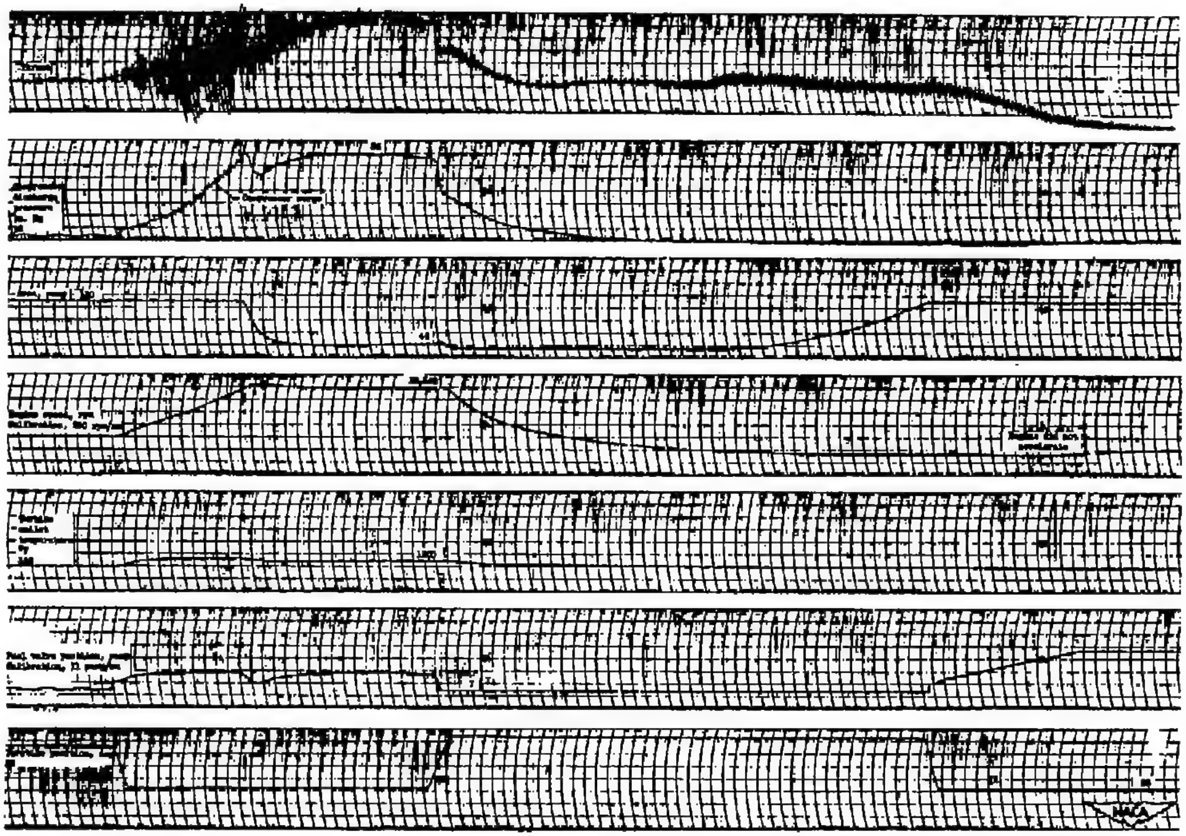
(i) Minimum fuel flow setting, 420 pounds per hour; power lever position, 85° to 22°; altitude, 25,000 feet.

Figure 6. - Continued. Transient operation of automatically controlled engine at a nominal ram pressure ratio of 1.2.



(j) Minimum fuel flow setting, 350 pounds per hour; power lever position, 84° to 22°; altitude, 25,000 feet.

Figure 6. - Continued. Transient operation of automatically controlled engine at a nominal ram pressure ratio of 1.2.



(k) Minimum fuel flow setting, 420 pounds per hour; power lever position, 32° to 85° to 20° to 85°; altitude, 25,000 feet.

Figure 6. - Continued. Transient operation of automatically controlled engine at a nominal ram pressure ratio of 1.2.

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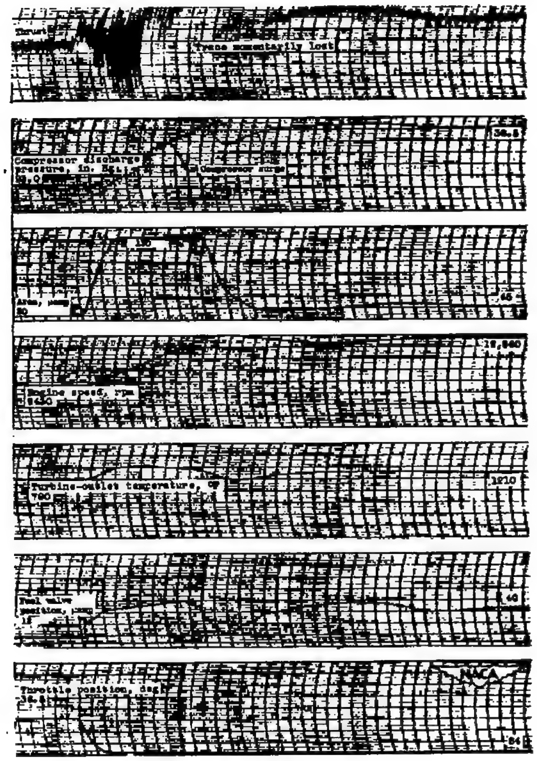
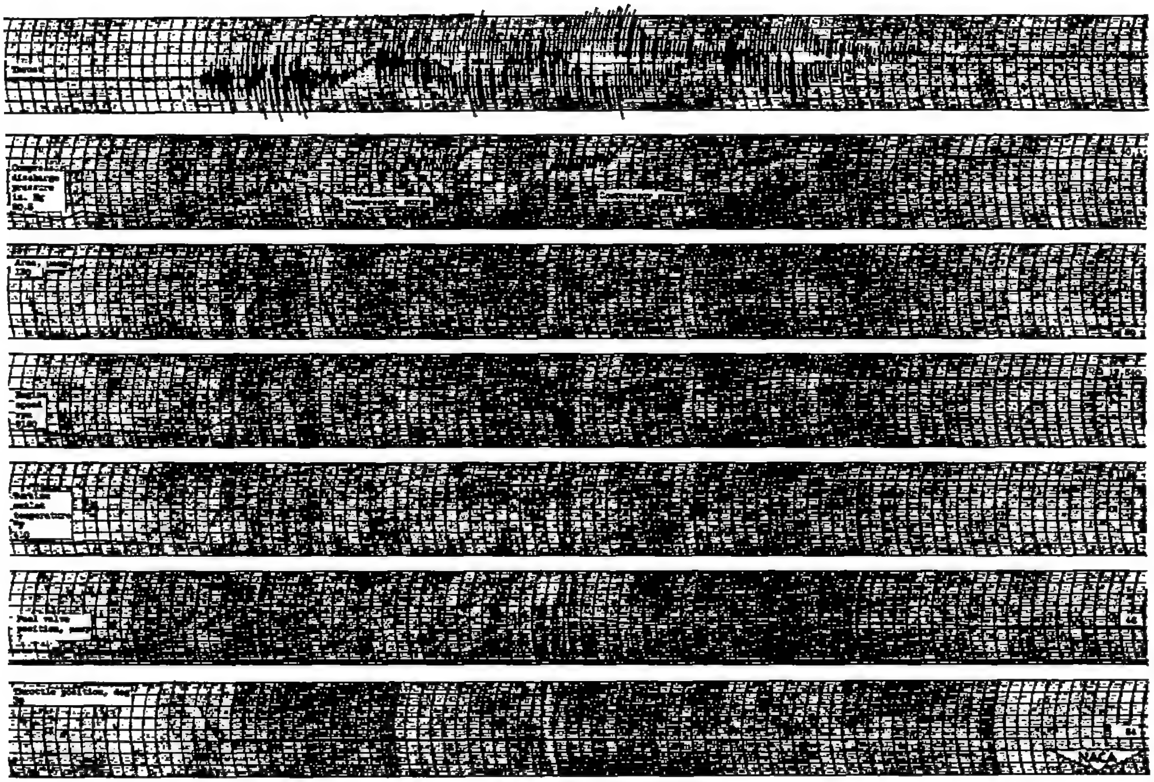


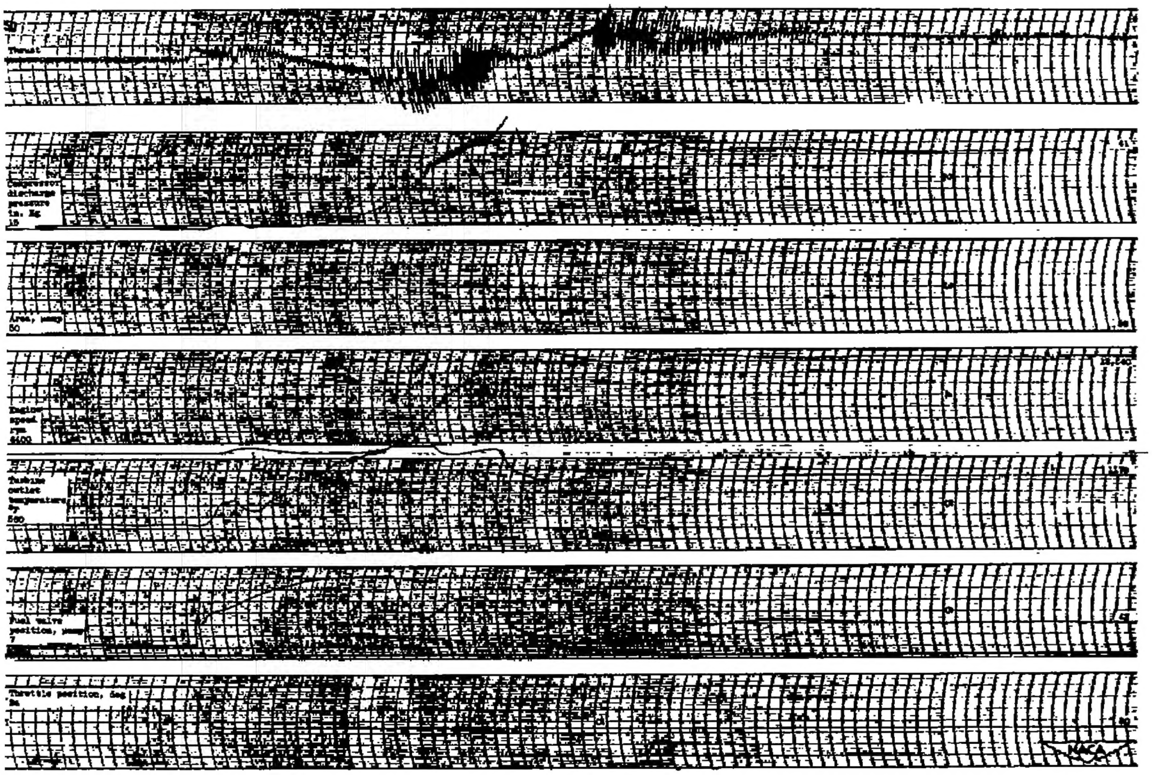
(1) Minimum fuel flow setting, 550 pounds per hour; power lever position, 36.5° to 84°; altitude, 35,000 feet.

Figure 6. - Continued. Transient operation of automatically controlled engine at a nominal ram pressure ratio of 1.2.



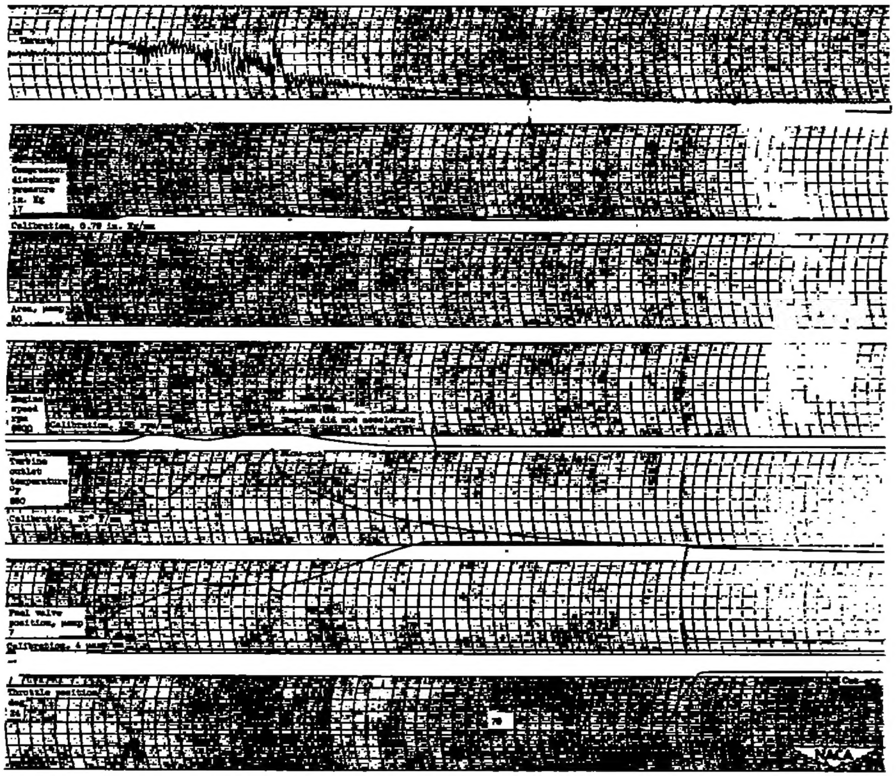
(m) Minimum fuel flow setting, 420 pounds per hour; power lever position, 39° to 84°; altitude, 35,000 feet.

Figure 6. - Continued. Transient operation of automatically controlled engine at a nominal ram pressure ratio of 1.2.



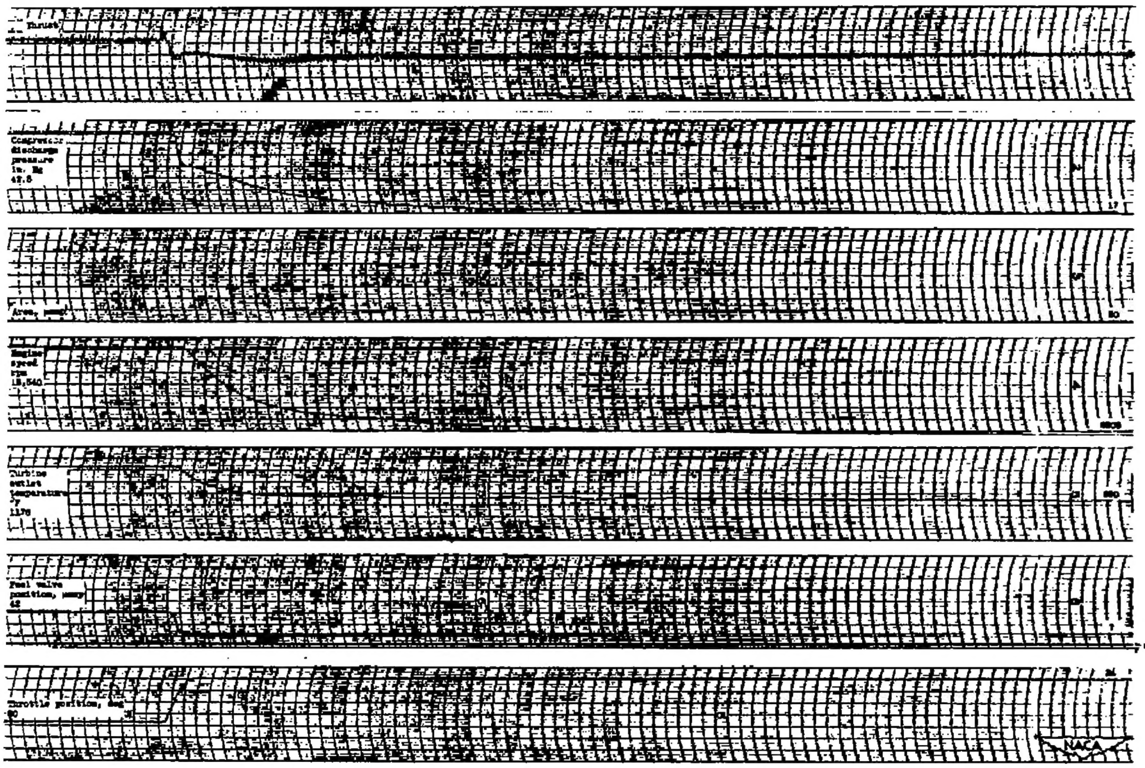
(n) Minimum fuel flow setting, 420 pounds per hour; power lever position, 25° to 84°; altitude, 35,000 feet.

Figure 6. - Continued. Transient operation of automatically controlled engine at a nominal ram pressure ratio of 1.2.



(o) Minimum fuel flow setting, 420 pounds per hour; power lever position, 25° to 84° to cut-off; altitude, 35,000 feet.

Figure 6. - Continued. Transient operation of automatically controlled engine at a nominal ram pressure ratio of 1.2.



(p) Minimum fuel flow setting, 420 pounds per hour; power lever position, 84° to 25°; altitude, 35,000 feet.

Figure 6. - Concluded. Transient operation of automatically controlled engine at a nominal ram pressure ratio of 1.2.

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SECURITY INFORMATION

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